Searches for Fourth Generation Charged Leptons

Linda M. Carpenter, Arvind Rajaraman and Daniel Whiteson[1]

[1]*Department of Physics and Astronomy*
University of California, Irvine, CA 92697

We study the production and decay of fourth generation leptons at the Large Hadron Collider (LHC). We find that for charged leptons with masses under a few hundred GeV, the dominant collider signal comes from the production through a W-boson of a charged and neutral fourth generation lepton. We present a sensitivity study for this process in events with two like-sign charged leptons and at least two associated jets. We show that with $\sqrt{s} = 7$ TeV and 1 fb^{-1} of data, the LHC can exclude fourth generation charged leptons with masses up to 250 GeV.

PACS numbers:

I. INTRODUCTION

One of the simplest possibilities for physics beyond the Standard Model is a fourth generation of fermions. Since these particles get masses from electroweak symmetry breaking, their masses must lie at the electroweak scale, and thus these particles are expected to be accessible to present and upcoming collider searches. Precision measurements constrain but do not exclude the parameter space for the fourth generation; with appropriate mass differences in the quark sector, a fourth generation is consistent with current electroweak precision data [1–3].

Direct searches at the Tevatron have constrained the fourth generation t' mass to be ≥ 335 GeV [4], and the b' mass is constrained to be ≥ 385 GeV [5]. Many LHC search analyses for fourth generation quarks have also been performed (for example [6–8]). However, experimental limits on the corresponding fourth generation lepton sector from hadron colliders have not been widely explored until recently [9].

The most important constraints on the fourth generation lepton sector currently come from LEP [11, 12]. If the fourth generation neutrinos can decay to SM particles through charged current interactions, they may be as light as 60 GeV [13]. Similarly, bounds on unstable fourth generation charged leptons are ~ 100 GeV [11]. As we shall see, these bounds can be considerably improved at the LHC, even with just 1 fb^{-1} of data.

The masses in the lepton sector of the fourth generation are parametrized by independent Dirac masses for the fourth generation charged leptons and neutrinos, as well as a Majorana mass for the right handed neutrino. The presence of both Majorana and Dirac masses for neutrinos means that in general there are two independent neutrino mass eigenstates N_1 and N_2, with corresponding masses M_1 and M_2. Furthermore, the charged lepton has an independent mass M_L. There are thus many possibilities for the mass spectrum in this sector.

Here we consider the scenario where the lighter neutrino N_1 is the lightest fourth generation lepton. This neutrino can then only decay through the process $N_1 \to W\ell$. Since the neutrino is a Majorana particle, it can decay equally to $W^-\ell^+$ and $W^+\ell^-$; thus when a pair of fourth generation leptons are produced, we expect the decay products to produce like-sign dileptons – a very distinctive signature – half of the time. This can be used to significantly suppress backgrounds at hadron colliders.

In previous work [14, 15], the same-sign dilepton signature was proposed and used to study the sensitivity of fourth generation neutrino searches at hadron colliders. However, these analyses assumed that charged leptons were quite heavy, and only the fourth generation neutrinos N_1, N_2 could be produced. In this work, we extend these analyses to include the charged lepton.

We will begin the next section by presenting the model that we consider, and discussing the production and decay of fourth generation leptons at the LHC. We find that the dominant production rate is that of charged lepton-neutrino through the process $qq' \to W \to LN_1$. We also find that even for this very simple process the final state topology is
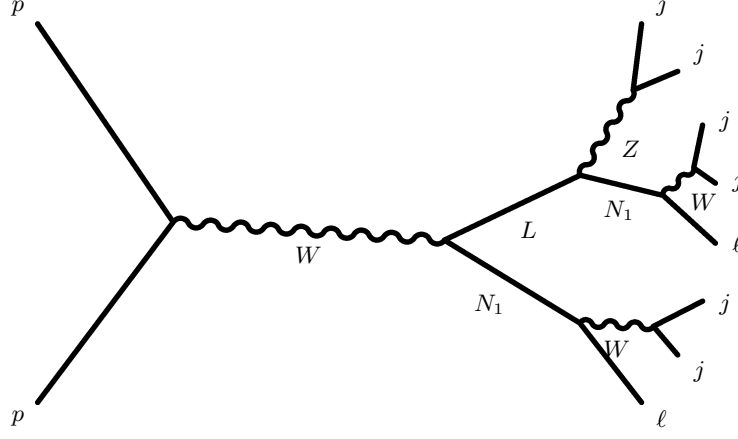
FIG. 1: Feynman diagram of the production and decay of LN_1 pair.

quite complex, since the leptons decay in a process $LN_1 \to WWW\ell\ell$, where half the time the leptons are same sign.

We then analyze the sensitivity of the LHC to fourth generation leptons in the channel with two like sign dileptons accompanied by two or more jets. Our sensitivity study shows that the 7 TeV LHC can exclude charged leptons with masses up to 250 GeV or better, even with just 1 fb^{-1} of data. We conclude with a discussion of future directions.

II. FOURTH GENERATION MASSES AND INTERACTIONS

We will be following the notation of [16].

We are considering an extension to the standard model by a fourth generation of fermions. To be completely general we include both Dirac and Majorana masses for the left- and right-handed neutrinos. The neutrino mass matrix may then be written as

$$\mathcal{L}_m = -\frac{1}{2}\overline{(Q_R^c N_R^c)} \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c. \tag{1}$$

where $\psi^c = -i\gamma^2\psi^*$. This theory contains two Majorana neutrinos N_1, N_2 with mass eigenvalues

$$M_1 = -(M/2) + \sqrt{m_D^2 + M^2/4}$$
$$M_2 = (M/2) + \sqrt{m_D^2 + M^2/4}$$

In addition, there is a Dirac mass term for the fourth generation lepton, $M_L \overline{L} E_R$, where L is the left handed doublet, and E_R is the right handed singlet.

The leptons couple to the gauge bosons through the interaction term

$$\mathcal{L} = g Z_\mu J^\mu + (g W_\mu^+ J^{\mu+} + c.c)$$

where

$$J^\mu = \frac{1}{2\cos\theta_W}(-c_\theta^2 \bar{N}_1 \gamma^\mu \gamma^5 N_1 - 2is_\theta c_\theta \bar{N}_1 \gamma^\mu N_2 - s_\theta^2 \bar{N}_2 \gamma^\mu \gamma^5 N_2))$$

$$J^{\mu+} = c_i \overline{(c_\theta N_1 - is_\theta N_2)} \gamma^\mu l_L^i \; + \frac{1}{\sqrt{2}} \overline{(c_\theta N_1 - is_\theta N_2)} \gamma^\mu L$$

where c_i are analogous to the CKM matrix elements. Here we have defined the mixing angle

$$\tan\theta = M_1/m_D$$

Since the parameters are not predicted theoretically, in principle either N_1 or L could be the lightest state (by construction N_1 is lighter than N_2). In the following analysis we will consider the scenario where the lightest fourth generation particle is N_1. It would be interesting to consider the case where the charged lepton is the lightest new state; we leave this for future work. For the moment we also assume that the mass of the heavier neutrino N_2 is greater than that of the charged lepton; later we will discuss the other situation when $M_2 < M_L$.
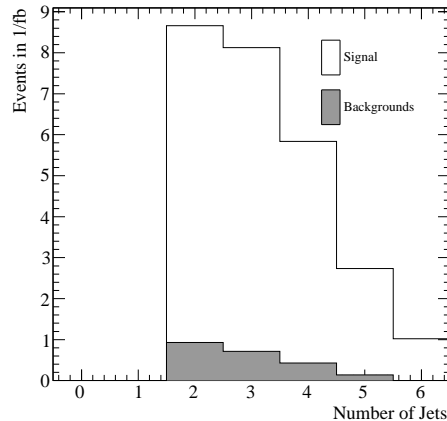
FIG. 2: Distribution of expected jet multiplicity in 1 fb^{-1} of data at the point $M_1 = 100$, $M_L = 200$ after selection of like-sign dileptons and at least two jets.

At hadron colliders, we can either pair produce leptons through the processes $q\bar{q} \to Z \to N_i N_j$ and $q\bar{q} \to Z \to L^+ L^-$, or we may produce a neutrino and charged lepton through the process $q_i \bar{q}'_j \to W \to N_i L$. At the LHC, we have many more W's than Z's, due to the preponderance of u-quarks and d-antiquarks in a proton-proton collision. This implies that if the charged lepton mass is comparable to the neutrino mass, the production rate of a charged lepton and neutrino through the W-boson will be much larger than the pair production rate through a Z. In fact, the typical production cross sections for charged lepton-neutrino production are found to be $10^{-1} - 10^{-2}$ pb, which are greater than the pair production rates by almost two orders of magnitude. We shall therefore ignore the pair production processes in the rest of our analysis.

We begin by considering the case where the charged lepton is produced along with the lighter neutrino through the process $pp \to W \to L N_1$. Since the mixing between the fourth generation and the first three generations is small (as required by precision experiments [18]), L will decay dominantly through the process $L \to W N_1$. N_1, on the other hand, can only decay through the process $N_1 \to \ell W$ where ℓ is one of the three leptons of the Standard Model.

The precise decay mode is controlled by the magnitude of the mixing angles. For simplicity, we assume that the mixing with one of the three SM leptons dominates, and therefore that all $N_1 \to \ell W$ decays will proceed to the same flavor of SM lepton.

The complete process that we consider is thus $pp \to L N_1 \to W N_1 N_1 \to WWW\ell\ell$, where the two charged leptons are the same flavor, and in half the cases are of the same sign. The W's tend to decay hadronically; we therefore obtain two leptons with multiple jets. Note that though the underlying physics is quite simple, our process can yield an eight body final state.

In general, we should also include production of $L N_2$. The production rate for this process will be somewhat lower because of the higher N_2 mass. The N_2 decays either as $N_2 \to L W$ or $N_2 \to N_1 Z$; in either case, we again get a signature of two leptons with additional jets, which increases the sensitivity of our search. We shall not include this production process in our analysis; our bounds will therefore be conservative.

III. SENSITIVITY ANALYSIS

We will focus on the $\ell^\pm \ell^\pm$ + multijets signature. A histogram of jet multiplicities for a benchmark point is shown in Figure 2. For example, for our benchmark point we expect 16 events per fb^{-1} which contain 2 or more jets.

At the LHC, the largest backgrounds to the $\ell^\pm \ell^\pm$ + multijets signature come from $W\gamma$ or WZ production or misidentified leptons either from semi-leptonic $t\bar{t}$ decays or direct $W+$ jets production. The LHC contains an additional process which was negligible at the Tevatron, $qq \to W^\pm W^\pm q' q'$, which directly produces the $\ell^\pm \ell^\pm jj$ signature. We calculate the size and kinematics of each contribution using MADGRAPH [19] and BRIDGE [20], and use PYTHIA [21] for showering and a version of PGS [22] tuned to describe the expected performance of the ATLAS detector. Figure 2 shows the expected background as a function of jet multiplicity.

Following [14], we look at events with $N_{jet} > 2$ with like-sign dileptons. We impose the following cuts:

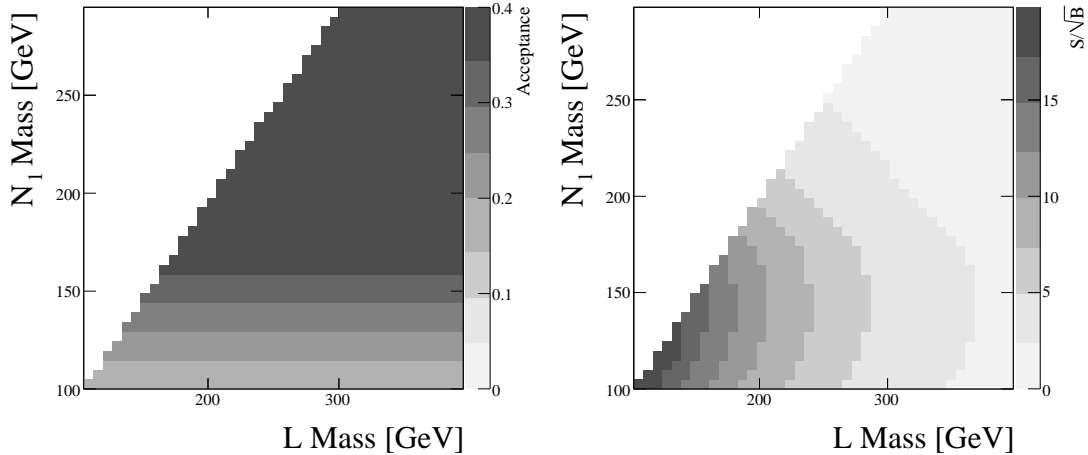- two isolated like-sign leptons of the same flavor

FIG. 3: Left, search acceptance over the $M_1 - M_L$ plane. Right, a simple significance metric, $N_{signal}/\sqrt{N_{background}}$ in 1 fb^{-1} of data.

- both lepton $p_T > 25$ GeV/c.

- at least two jets with $E_T > 20$ GeV.

Figure 3 shows the calculated acceptances for these cuts in the $M_1 - M_L$ mass plane. The acceptances range from 0.15 to 0.4. The efficiencies are relatively independent of the charged lepton mass; they however drop as N_1 becomes less massive, because all the decay products become soft. Figure 3b gives an approximate figure of merit $S/\sqrt{B}$ per fb^{-1}. Note that the range of masses $M_1 > M_L$ is excluded by assumption.

To extract more sensitivity and identify the mass scale, we reconstruct the observed N mass from the $\ell j j$ objects, following the procedure in [14]. We perform a binned likelihood fit in the reconstructed N mass, and use the unified ordering scheme [23] to construct frequentist intervals. We include an overall 100% systematic uncertainty on the background rate as well as an uncertainty that describes our lack of understanding of the rate of radiation.

The final expected exclusion ranges in the $M_1 - M_L$ plane are shown in Fig. 4. We see that for 1 fb^{-1} we may discover or exclude charged leptons of masses up to 250 GeV. For some values of M_1, charged leptons may be excluded up to masses of 320 GeV.

IV. CONCLUSIONS

We have studied the fourth generation leptonic sector, considering the case where both the charged lepton L and the fourth generation neutrinos N_1, N_2 are accessible to colliders. In this situation, the largest production cross section of fourth generation particles is through LN_1 production. The decay of this pair leads to a distinctive final state topology of same-sign dilepton production in association with multiple jets. We have shown that in this channel, an LHC search at 7 TeV with 1 fb^{-1} of data can exclude fourth generation charged leptons with masses up to 250 GeV. This is a significant improvement on present constraints.

In the analysis above, we have assumed that the mass of N_2 is larger than that of the charged lepton. However, the case that N_2 is lighter than L is expected to be very similar. In that case, there may be sometimes be an N_2 in the L decay chain, $LN_1 \rightarrow WN_2N_1 \rightarrow WZN_1N_1$. We still get like sign dileptons from the N_1 decays, plus additional jets from the extra Z. We expect the efficiencies for this search to be the same or slightly better than the one we have considered, as there will be more jets. Our bounds are only expected to be improved in this scenario.

It is also interesting to consider ways of distinguishing this signal from other models of new physics with same-sign dilepton signals, as for example pair production of N_1 in the situation when L is heavy. One possibility is to use the feature of the LN final states that the jet multiplicity falls off slowly. For example, Figure 2 shows that there are 16 event per fb^{-1} with 2 jets or more, while there are still 10 events per fb^{-1} with 4 jets or more. Indeed, as shown in Figure 4, if one requires a four jets plus like-sign dilepton signal instead of a two jet plus dilepton signal, one can still exclude charged leptons with masses up to 200 GeV. The presence of many jets may therefore be a useful feature in
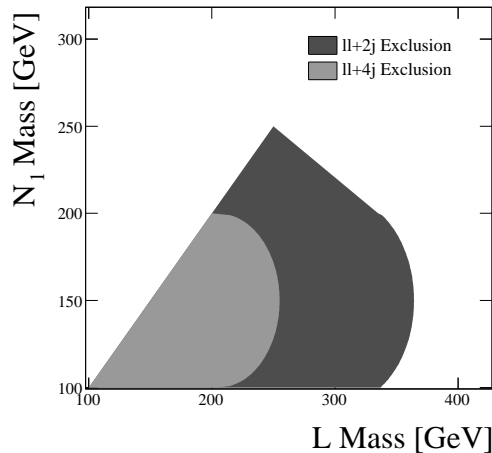
FIG. 4: Expected exclusion in $M_1 - M_L$ mass plan for 1 fb^{-1} for the dilepton+ 2j and dilepton + 4j selections.

distinguishing the production of LN from other similar processes. It would be interesting to see how strongly the jet multiplicity constrains the underlying process.

There are several further directions for study. In particular, it would be interesting to consider the case where the charged lepton is the lightest of the fourth generation leptons. Another possibility is for the lightest neutrino N_1 to be stable. In this scenario, instead of dileptons, we obtain signatures with a large amount of missing energy, which may be challenging to observe. We hope to return to these analyses in future work.

V. ACKNOWLEDGMENTS

[1] H. J. He, N. Polonsky and S. f. Su, Phys. Rev. D **64**, 053004 (2001) [arXiv:hep-ph/0102144].
[2] G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, Phys. Rev. D **76**, 075016 (2007) [arXiv:0706.3718 [hep-ph]].
[3] J. Erler and P. Langacker, Phys. Rev. Lett. **105**, 031801 (2010) [arXiv:1003.3211 [hep-ph]].
[4] [CDF Collaboration], CDF10110, http://www-cdf.fnal.gov/physics/new/top/confNotes/tprime_CDFnotePub.pdf
[5] [CDF Collaboration], CDF10243, http://www-cdf.fnal.gov/physics/new/top/2010/tprop/bprime_public/conference_note.pdf
[6] V. E. Ozcan, S. Sultansoy and G. Unel, Eur. Phys. J. C **57**, 621 (2008).
[7] O. Cakir, H. Duran Yildiz, R. Mehdiyev and I. Turk Cakir, Eur. Phys. J. C **56**, 537 (2008) [arXiv:0801.0236 [hep-ph]].
[8] B. Holdom, JHEP **0708**, 069 (2007) [arXiv:0705.1736 [hep-ph]].
[9] V.E. Ozcan *et al.*, J. Phys. G: Nucl. Part. Phys. 36 (2009) 095002
[10] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)
[11] P. Achard *et al.* [L3 Collaboration], Phys. Lett. B **517**, 75 (2001) [arXiv:hep-ex/0107015].
[12] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **99**, 121801 (2007) [arXiv:0704.0760 [hep-ex]].
[13] L. M. Carpenter and A. Rajaraman, arXiv:1005.0628 [hep-ph].
[14] A. Rajaraman and D. Whiteson, Phys. Rev. D (2010) [arXiv:1005.4407 [hep-ph]].
[15] A. Rajaraman and D. Whiteson, Phys. Rev. D **81**, 071301 (2010) [arXiv:1001.1229 [hep-ph]].
[16] Y. Katsuki, M. Marui, R. Najima, J. Saito and A. Sugamoto, Phys. Lett. B **354**, 363 (1995) [arXiv:hep-ph/9501236].
[17] C. T. Hill and E. A. Paschos, Phys. Lett. B **241**, 96 (1990).
[18] M. S. Chanowitz, Phys. Rev. D **79**, 113008 (2009) [arXiv:0904.3570 [hep-ph]].
[19] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].
[20] P. Meade and M. Reece, arXiv:hep-ph/0703031.
[21] T. Sjöstrand *et al.*, Comput. Phys. Commun. **238** 135 (2001).
[22] M. Carena *et al.* arXiv:hep-ph/0010338v2
[23] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).